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THE MEASUREMENT OF REACTIVE POWER

POWER measurements of alternating current systems while generally concerned with the in-phase components of the apparent power (volt amperes) must evaluate the quadrature power component in order to completely analyze the power demands of the system.

The power resulting from the applied potential and the component of the current in phase with it, termed the active power, is measured in terms of watts, kilowatts or megawatts and the methods for determining this quantity are well known and in general use. This is the power dissipated in the resistance or equivalent resistance of the circuit, and in a single phase circuit, is equivalent to I^2R or $EI \cos \phi$ for sine wave form where

E = Voltage, volts rms
I = Current, amperes rms
ϕ = Phase angle between E and I
R = Equivalent resistance ohms
X = Reactance, ohms.

The power resulting from the applied potential and the component of the current in quadrature with it, equal to I^2X or $EI \sin \phi$ for sine wave form, while of considerable importance in the operation of power generating equipment is not so well known as the active power. Although this power does not produce work, it is essential in producing the conditions which bring about work. In order for a transformer to function, or a motor to run, it is necessary to magnetize the core or field. The component of the current which produces the magnetic field is in quadrature or 90 degrees out of phase with the applied potential and in time phase, lagging.

This quadrature power has been termed the wattless power, wattless component, reactive power, reactive volt amperes, volt amperes reactive and is expressed in terms of the unit, the VAR. This terminology was adopted at the International Electrical Convention at Stockholm in 1930. The word VAR is the abbreviation for volt amperes reactive. The measurement of this quantity is not difficult and there are various methods for determining the quadrature power.

Methods of Measuring Quadrature Power

One method consists of measuring the potential, current and the phase angle: the quadrature power is then calculated from the equation $EI \sin \phi$ for a single phase circuit having a sine wave form. It is essential that these measurements be made simultaneously, requiring three instruments and three observers for single phase measurements. It must be remembered that phase angle meters such as power factor meters for use on single phase circuits are critical with respect to frequency and that the usual polyphase meters are correct only on balanced loads.

A second method of measuring the quadrature power requires the measurement of the potential, current, and the active power. Quadrature power for sinusoidal wave form can then be calculated from the relation,

$$\text{Vars} = \sqrt{(\text{Volt Amperes})^2 - \text{Watts}^2}.$$

The active power is very conveniently measured by means of an electrodynamometer wattmeter.

The electrodynamometer in its best form consists of a stationary coil system which produces a magnetic field and a movable coil mounted to a pivoted staff which also carries a pointer. The movable coil rotates in the magnetic field of the stationary coils and the torque producing the angular deflection is proportional to the product of the components of the ampere turns of the movable coil and the ampere turns of the field coils which are in phase with each other. The movable coil, together with the necessary series resistance, is connected across the line and its current is proportional to and substantially in phase with the potential applied and the instrument indicates the in-phase product of current and potential or active power. Figure 1 is a vector diagram of the voltage and current conditions for a single phase circuit wherein *OM* represents the current in the movable coil which is in phase with the applied potential and *OF* the current in the field coil. *OA* is the component of the field coil current in phase with the movable coil current and is equal to *OF* $\cos\phi$. It is this current which causes the movable system of the electrodynamometer to deflect when connected to measure watts.

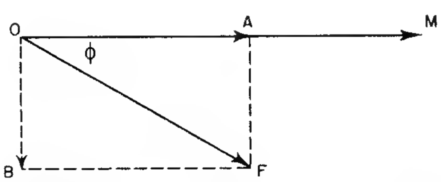


Figure 1—Typical vector diagram of voltage and current relations in single phase circuits.

The quadrature power can be directly and conveniently measured with the electrodynamometer by shifting the phase of the current in its movable coil 90 degrees so as to bring it into phase with the quadrature component of the current in its field coils. Referring to Figure 1, the magnetizing or quadrature component of the current which must be considered when measuring vars is represented by the vector *OB* which is equal to *OF* $\sin\phi$.

The methods for bringing about this phase shift are described in the paragraphs which follow.

Single Phase Circuits

The current in the potential circuit of the electrodynamometer is practically in phase with the potential applied.

We can shift this current nearly 90 degrees by substituting a series reactance for the series resistance in the movable coil circuit. By using a tapped reactance and an auxiliary shunt resistance, as shown in Figure 2, we can obtain a true 90 degree relation.

In order to adjust the instrument, an adjustable resistance is inserted in series with its potential circuit. It is then connected, as for measuring watts, to a lamp bank load at the potential, current and frequency desired.

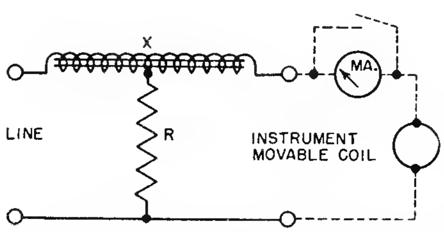


Figure 2—Circuit of reactor for single phase varmeter.

The resistance is adjusted to give full scale reading when the potential current and frequency are as desired for full scale watts. A low resistance milliammeter is connected in series in the potential circuit. The most satisfactory milliammeter for this purpose is a thermocouple type. The potential circuit current for full scale is then recorded. The series resistance is then replaced by an adjustable reactor and a shunt resistor connected to a suitable tap on the reactor as shown in Figure 2. The reactor *X* and the resistor *R* are adjusted so that with the above potential, load current and frequency, the potential circuit current is restored to the recorded value and with the milliammeter shorted the instrument under adjustment reads zero. The current of the potential circuit has now been made to lag 90 degrees behind the applied potential and becomes in-phase with the quadrature or magnetizing current described. The instrument is now correctly adjusted to measure vars.

From the above it is quite evident that correct indications will be obtained only when the frequency is the same as that used in the adjustment. Any deviation in frequency will result in an error.

The same instrument may be used to measure either watts or vars by connecting as shown in Figure 3. A series resistance and a series reactance are each adjusted so that with the former in its potential circuit the instrument measures watts, and with the latter in circuit it measures vars. R_1 represents the series resistance used when measuring watts.

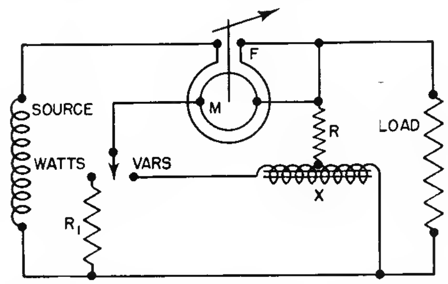


Figure 3—Diagram showing connection of instrument for measuring watts or vars in single phase circuit.

Two Phase Circuits

A two phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by 90 degrees. The two sources of potential may be insulated or may have a common terminal, the former is known as two phase four-wire circuit and the latter as two phase three-wire circuit.

Either circuit may be treated as two single phase circuits utilizing instruments and measurements as described under single phase circuits. The total active or reactive power will be the algebraic sum of the respective powers measured for the two circuits.

In order to reduce the number of instruments and still obtain the correct indication of power, it is more convenient to use an electrodynamometer having two elements. This instrument essentially combines two single element instruments with the movable potential coils of each element mounted to a common pivoted staff carrying a pointer which moves

over a common scale. The total torque developed is the algebraic sum of the torques produced in the elements. The scale may be graduated, and the indications of the pointer in reference to this scale will be in terms of the total power.

The current and voltage distribution of a two phase system may be represented by vectors as shown in Figure 4. *C1* represents the voltage in one phase and *C2*, the voltage in the second phase. These potentials are considered as balanced when they are equal and displaced by 90 degrees.

If *CA* represents the current as measured for phase 1, the component of this current in phase with its potential will be CA_1. This component of the total current produces

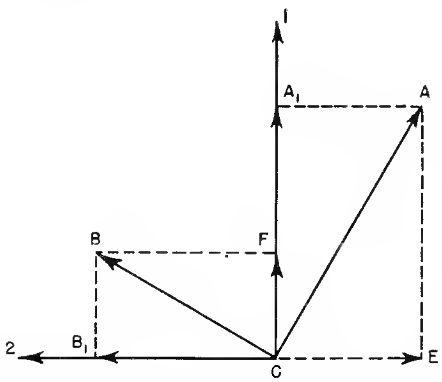


Figure 4—Typical vector diagram of current and voltage relations of a two phase system.

torque in the element of the electrodynamometer when measuring watts. The component of the total current which is in quadrature with its potential will be *CE*, and it is this component of the current which produces torque in the element of the electrodynamometer when measuring vars. Likewise, the component of the current *CB* which is in phase with its potential will be CB_1 and the component in quadrature will be *CF*.

If we connect element 1 of a two-element electrodynamometer to phase 1 and element 2 to phase 2 as shown in Figure 5, the torques developed in each element will be in proportion to the potential applied to the movable coil of each element and the component of the current, in the stationary, or field coil, which is in phase with its potential.

Referring to Figure 4, these components will be CA_1 for element 1 in phase with *C1*, and CB_1 for element 2 in phase with *C2*. The indication of the common pointer on the scale will therefore be in terms of the active power or watts.

indication, that is, up scale indication of lagging power factor.

Similarly the reactive power of phase 2 may be determined by connecting element 2 to the potential *C1* which is in phase with the quadrature current component *CF*. Note

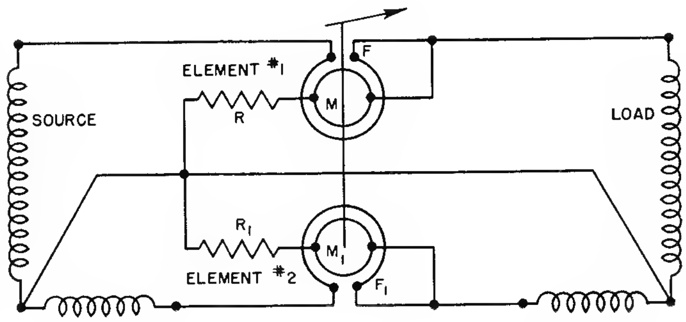


Figure 5—Diagram of connections for a two-element electrodynamometer for measuring vars in a two phase three-wire circuit.

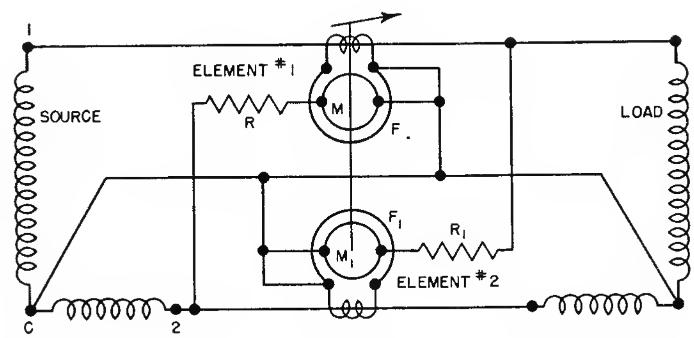
When connected, as shown in Figure 5, the quadrature component of the current in the field of element 1, represented by *CE* in Figure 4, will develop no torque with the movable coil. Likewise, the quadrature component of the current in the field of element 2, represented by *CF* in Figure 4, will develop no torque with its movable coil.

In order to measure the reactive power of phase 1, element 1 must be connected to a potential which is in phase with the quadrature component of the current in the field coil associated with that element. This condition may be readily obtained by using potential *C2* which is in phase opposition with the quadrature current component *CE*. It will be necessary when making this

that vectors *C1* and *CF* are in the same direction, indicating that it is not necessary to reverse connections to obtain an up-scale indication. These connections are shown in Figure 6 in which the potential connections for element 1 are transferred to *C2* and reversed. The use of current transformers in the field circuits is suggested in order that the field and movable coils of each element may be connected together to avoid electrostatic effects.

By virtue of the balanced potentials of the circuit, there is no change in magnitude when the voltage connections are shifted and the instrument can be used to measure watts or vars simply by transposition of the proper connections. See Figure 7.

Figure 6—Diagram of connections for a two-element electrodynamometer for measuring vars in a two phase three-wire circuit.



transposition to reverse either the potential connection to the moving coil or the current connection to the field coil to preserve the direction of

Two phase four-wire circuits may be treated similar to two phase three-wire circuits except that the insulation between the phases must

be preserved. If the potential coils of the wattmeter are connected together and brought out to three binding posts, it is necessary to use two potential transformers as shown in Figure 8. Current transformers are suggested so that ground connections may be made to relieve electrostatic effects and protect the instrument.

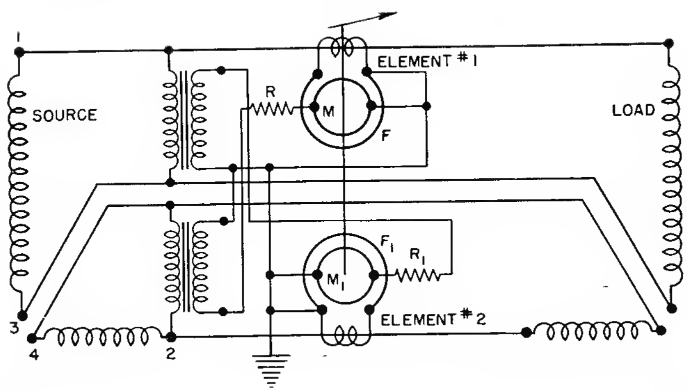


Figure 8—Diagram of connections for a two-element electrodynomometer for measuring vars in a two phase four-wire circuit.

Instrument manufacturers generally find it more satisfactory to insulate the potential circuits of varmeters, bringing the connections to the potential coils to four binding posts. The potential transformers are then unnecessary except when the line potentials are higher than the self-contained ranges provided.

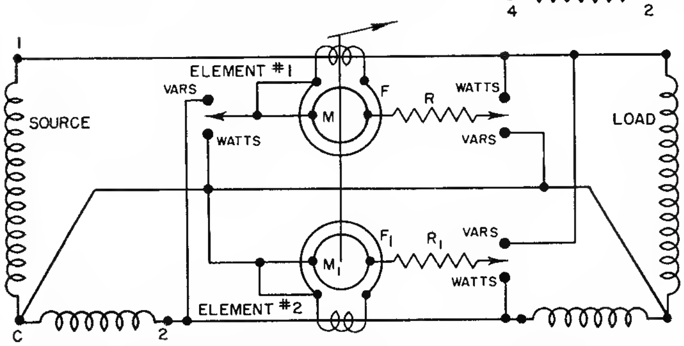


Figure 7—Diagram of connections for a two-element electrodynometer for measuring watts or vars in a two phase three-wire circuit.

A discussion of power measurements of three phase systems and the use of auto-transformers as phase-shifting devices will appear in a subsequent issue of WESTON ENGINEERING NOTES.

E. N. —No. 24 —*A. F. Wolferz*

SPECIAL LOAD CIRCUITS FOR USE WITH THE WESTON PHOTOELECTRIC CELL

THE barrier layer Photoelectric Cell consists essentially of a selenium layer upon which a transparent electrical collector electrode is deposited. When exposed to light, the selenium emits electrons which are projected through the "barrier layer" and collected by the transparent electrode, to establish a proportional current in the external circuit.

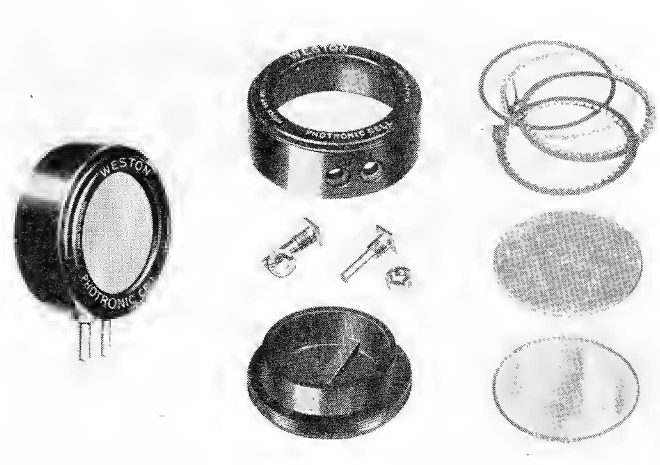
As it is a self-contained converter of incident light energy to electrical energy, no batteries are ordinarily required and it is particularly adaptable to small portable light-measuring devices. Typical of these is the photographic exposure meter, which is in extensive popular use, and the illumination meter used to monitor artificial lighting for proper illumination. An exploded view of the Weston Photoelectric Cell illustrating the barrier layer, collector rings and housing is shown in Figure 1.

For most light measurements, including photography, a nominal order of accuracy is sufficient and it is not as important to operate the photoelectric cell under ideal conditions as to simplify the instrument. But where the measurement problem is sufficiently more critical in character to justify additional accessory equipment or adjustments, more ideal conditions of photocell load can be established with attendant improvements in performance. These can include a lower order of fatigue, a more linear output current-illumination relationship, a lower temperature coefficient, and better resistance to intense illumination.

Electrical Characteristics

The electrical characteristics of the photoelectric cell are described in Weston Technical Bulletin B-20-C which is referenced for performance details and limitations. For con-

Figure 1—An exploded view of the Weston Photoelectric Cell.



venience, the curves illustrating the dependence of illumination output and the temperature coefficient of output, upon the externally connected load resistance for a typical

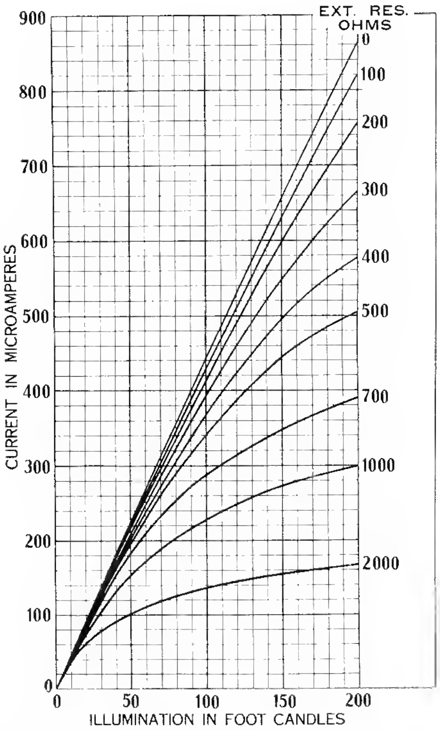


Figure 2—Effect of illumination and external resistance on current output of Type 3RR Cell. (Tungsten lamp at 2,700° K.)

average cell are reproduced in Figures 2 and 3. Note that in all cases it is desirable to have a low value of load resistance to obtain the most desirable operating charac-

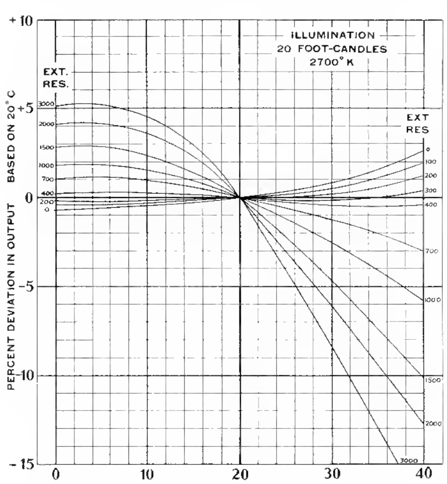


Figure 3—The effect of temperature on current output of Type 3 Cells at 20-foot candle illumination.

teristics. Unfortunately, sensitive microammeters with which the cell would ordinarily be used have a much higher order of resistance and the load is such that the cell operates in the less desirable performance regions of the curves. In the case of refined measurements, it is thus desirable to forego the convenient and simple direct-connected indicating microammeter and employ special circuits that will effectively maintain a lower order of external resistance.

Current Balance Circuits

The illuminated photocell is essentially a current source of finite resistance and as such it may be visualized as an internal potential and an internal resistance in series. When short circuited it will deliver a current through the short circuit equal to the potential divided by the resistance. If the short circuit is removed and the cell connected to an external current source having a polarity *aiding* the original cell current and a magnitude *equal* to the original cell current, the voltage appearing across the cell terminals

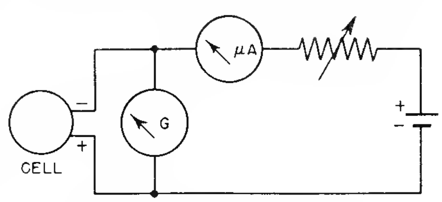
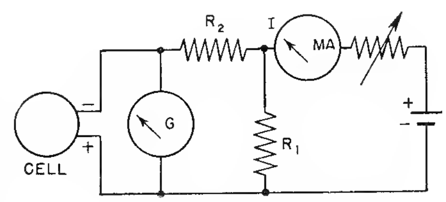


Figure 4—Current balance circuit.

will be the same as when short circuited, or zero. By this method the potential at the cell terminals has been artificially reduced to zero, and a condition of *effective* zero external resistance produced. Also the current supplied to the cell from the external current source is equal to the original short-circuited cell current, and may be used as a measure of the cell current which would result with zero external load resistance.

A simple practical circuit using this principle of current balance is shown in Figure 4. A nul galvanometer is included to indicate the balance condition of zero potential across the cell terminals. In operation the cell is illuminated and the external current source adjusted to produce a nul reading on the galvanometer. The microammeter then indicates the short-circuit cell current. The galvanometer need not have a low resistance because at balance its resistance is not an effective cell load, and it can have a high resistance and a high current sensitivity for maximum sensitivity to unbalance. The optimum condition is a galvanometer resistance of the order of the cell resistance shunted by the current source resistance, ordinarily several thousand ohms.

Figure 5 is a modification of the circuit of Figure 4 including an attenuator in the current source so that the indicated current is larger than the cell current by a known ratio. This arrangement is particularly adaptable to measurement of

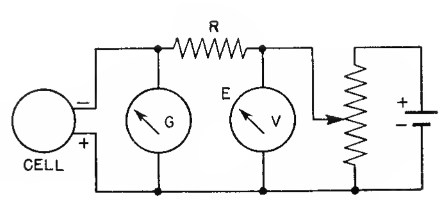


CELL CURRENT $= I \frac{R_1}{R_1 + R_2}$

Figure 5—Current balance circuit with attenuator.

low light levels resulting in a sensitivity comparable with that obtained from a suspension galvanometer without requiring a sensitive current measuring instrument. The resistor R_2 is effectively a galvanometer shunt and should be large compared with the resistance of the galvanometer.

The circuit of Figure 6 is a variation wherein the balancing current is derived from a source of known voltage. Its use relative to the preceding circuits is normally a matter of convenience.



CELL CURRENT $= \frac{E}{R}$

Figure 6—Current balance circuit using a variable voltage source.

Simplified Current Balance Circuit

By lowering the resistance of the current source and the voltage producing the current, the indicating microammeter will become partially responsive to the potential developed by unbalanced voltages across the cell. This effect may be used to indicate the balance condition as shown in Figure 7 which is similar to the circuit of Figure 4 except that the galvanometer is replaced by a normally open push button, and the resistance of the current source is low as the current is derived from a low fixed voltage.

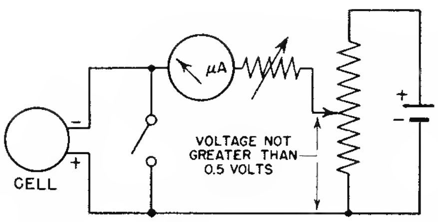


Figure 7—Simplified current balance circuit using a microammeter as the balance indicator.

In operation the current source is adjusted until operation of the push button produces no change in the microammeter reading. At this point the potential across the cell is zero and the currents are in balance.

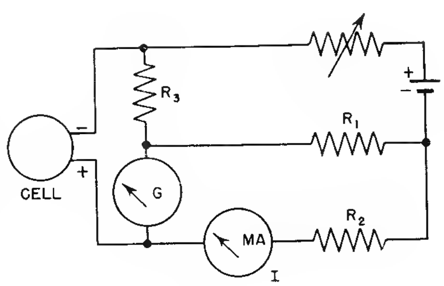
It is recommended that the voltage source be no larger than 0.5 volt to avoid damage to the cell and microammeter if the circuit is operated far from the balance point. In this circuit the polarity must be observed because the cell will be damaged by the injection of reverse currents.

Negative Resistance Circuits

From the curves of Figures 2 and 3 it is obvious that for some conditions it would be desirable if the external load resistance could be made less than zero, or negative in sign. For example the curve of output current against illumination is still not quite linear with zero applied resistance, due to a small unavoidable *internal* cell series resistance. While negative resistance does not exist in the form of a component resistor, the equivalent effect can be produced by a variation of the current balance principle.

Expressed simply, negative resistance presupposes that current passed through it will develop a voltage drop opposite in sign to the voltage drop across a positive resistance for the same current direction. Thus the same effect can be produced by deriving a similar voltage that varies with the circuit current in the same fashion, in any manner whatsoever.

The circuit of Figure 8 is the simple current balance circuit of Figure 4 to which has been added a second current branch R_1 passing current through a resistor R_3 in series with the galvanometer. The voltage drop of the second branch current through R_3 then has a polarity opposite in sign to that which would result if the normal cell output current were passed through a positive load resistance. Balance of the current source to a galvanometer nul will then develop a proportionate potential across the cell which is equivalent to a negative load resistance.



$R_1 = R_2$
R_3 = EXTERNAL RESISTANCE
(R_2 INCLUDES METER RESISTANCE)

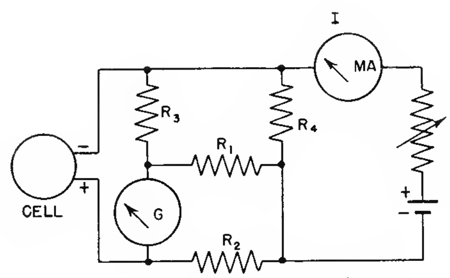
Figure 8—Negative resistance current balance circuit.

For convenience, the resistances of the two current branches R_1 and R_2 are made equal so that the current flowing through R_3 is equal to the cell current as indicated by the microammeter, and the R_3 will numerically equal the effective negative resistance.

Figures 9 and 10 are variations of the circuit of Figure 8, similar respectively to the variations included in Figures 4-6.

Theoretically, the photoelectric cell might be expected to become strictly linear in its output current-illumination relationship when the external negative resistance is numerically equal to its internal positive series resistance. The total load resistance should then be zero. Actually the internal series resistance is slightly non-linear and complete correction is not possible with a constant value of external resistance. Occasionally a specific cell will require a small positive load resistance for linearity, particularly over low illumination ranges. Thus no general optimum value of external resistance can be stated, but with most cells it is in the order of 50 to 2,000 ohms negative for low and high output cells respectively.

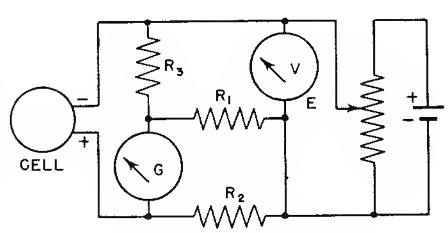
A determination of the optimum load resistance requires an illumination change of known ratio, preferably at levels including most of the desired range of illumination. This can be obtained by interposing a neutral filter of known density, or by moving a constant light source such as a lamp away from the cell a known distance. In the latter case the illumination ratio will be the



$$\text{CELL CURRENT} = I\,\frac{R_4}{2(R_1+R_3+R_4)}$$

WHERE: $R_1 = R_2$
R_3 = EXTERNAL RESISTANCE

Figure 9—Negative resistance current balance circuit with attenuator.



$$\text{CELL CURRENT} = \frac{E}{2(R_1+R_3)}$$

WHERE: $R_1 = R_2$
R_3 = EXTERNAL RESISTANCE

Figure 10—Negative resistance current balance circuit using a variable voltage source.

square of the distance ratio. The load resistance can then be varied experimentally until the output current ratio agrees with the illumination ratio, indicating an optimum load resistance for greatest linearity.

Differential Circuits

In many applications, particularly those involving transmission or absorption measurements, two cells are connected differentially to indicate the difference in current output. By this means a large measure of independence of light source variations can be realized because both cells are affected equally. For effective compensation in such a circuit both cells must have the same order of linearity or a differential output change will occur with equal change in illumination on each cell. The cells could be matched for linearity but this involves rather expensive selection as a production process, particularly when large quantities are required.

As an alternative in such cases, cells having only the same nominal order of linearity can be used if the cells are matched by an electrical means. A simple method is to curve the more linear cell of the pair to agree with the poorer cell by adding a small amount of external series resistance, as shown in Figure 11. The resistance is placed in series with the cell showing the greater increase of output upon an equal increase in the illumination of both, and is adjusted for the greatest independence of illumination change.

Automatic Potentiometers

The circuits of Figures 4 through 10 are particularly adapted to operation with automatic potentiometers wherein balance is automatically restored in response to galvanometer deflection. Typical of these potentiometers is the Weston Model 721, which can be connected to use the circuits of Figure 5 or 9. For potentiometers of the slide wire type, for example those normally used as recording pyrometers, the slide wire potential may be used as a current source and connected as shown in Figure 6 or 10.

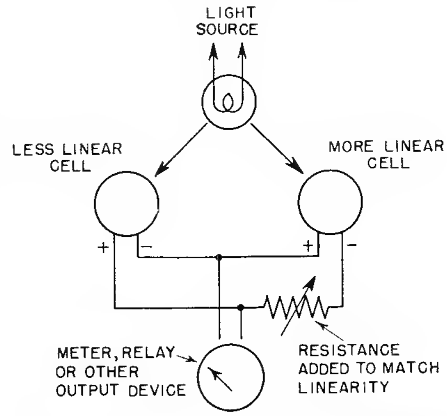


Figure 11—Matched linearity differential circuit.

E. N.—No. 25 —*R. W. Gilbert*

THE VU INDICATOR

THE VU indicator developed in 1938 has, over the intervening years, become the standard in radio broadcasting for monitoring and control of gain and loss in transmission lines. The value of this instrument results from its carefully controlled damping and speed. The damping is held to a pointer overswing of 1 to 1.5% while the speed of pointer deflection is 0.3 second ±10% to within 99% of final reading. Seldom have the dynamic characteristics of an entire series of indicating instruments been so rigorously specified and maintained. The VU indicator is a rectifier type instrument with a permanent magnet moving coil mechanism operated from a full wave bridge rectifier.

The VU indicator was developed for the broadcasting industry because by 1938 its growth made necessary one standard monitoring instrument. A definition of what the instrument indicated had to be evolved. To express the measurement, the designation VU was selected and defined as the relative strength in decibels from a reference level of 1 milliwatt fed into 600 ohms. The designation VU is a contraction of "volume unit" and is defined as the reading of this particular instrument on the circuit in question after having been calibrated on a sine wave source. The standard definition is incorporated in "American Recommended Practices for Volume Measurement of Electrical Speech and Program Waves," C 16.5-1942 of the American Standards Association.

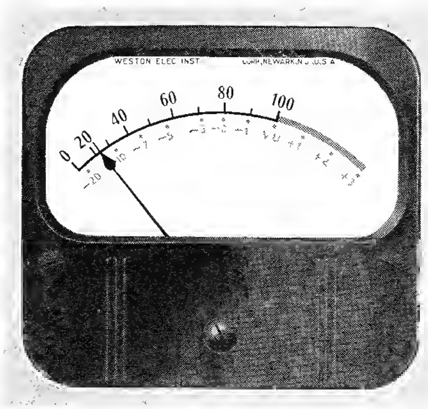


Figure 1—The Weston Model 862, Type 30B VU Meter.

The scale of the VU indicator is calibrated for both 0 to 100 per cent voltage and −20/0/+3 VU. The 0 to 100 per cent scale is provided for ease of monitoring since a per cent scale is easily read and useful to indicate per cent utilization of facilities or per cent modulation. The color of the scale is a special buff selected as the best compromise between high contrast and reduced eyestrain and fatigue. As the instrument is used both for monitoring and control of gain and loss in long line transmission, two different scales have evolved. Scale A stresses db or vu readings while scale B (Figure 1) stresses per cent.

Control of Dynamic Characteristics

To hold the speed and damping of the VU indicator to the close limits specified, it is necessary that the manufacturing controls be rigid. For example, every moving element, before being mounted within its magnetic system, is timed to determine if its speed is such that when mounted and adjusted for its

proper sensitivity and pointer overswing of 1 to 1.5%, the deflection time is 0.3 second ±10% to within 99% of final reading.

The care taken to secure its exact ballistics makes the instrument broadly useful in many fields allied to broadcast and communication. Among applications of the VU indicator other than for broadcast monitoring are: control of volume in record cutting, the study of supersonics, sound measurement of water depth, noise measurement and the study of transient phenomena in electronic circuits.

The VU indicator has been made in panel type instruments from 2½ inches to 7 inches in diameter. The basic requirements are that the inertia, torque and magnetic flux be such that the proper damping and speed be obtained with the necessary electrical characteristics. The smaller instruments require heavy moving systems while the large ones require light moving systems to obtain suitable moments of inertia. The current sensitivity of the VU indicator is high so that a large number of turns on the moving coil are necessary to obtain the high torque required for the necessary rapid speed of response. Then the flux in the air gap has to be high so that the closely controlled damping of the VU indicator is obtained.

The inertia, torque and magnetic flux are by no means independent of each other and the design of the VU indicator requires proper consideration of the mutual dependence of these factors.

Electrical Characteristics

The VU indicator is adjusted to 163.7 microamperes alternating current at the 0 VU scale mark, with the full scale (+3 VU) current being approximately 240 microamperes alternating current. The voltage adjustment is always made with 3,600 ohms in series. With this 3,600 ohms in series, the overall voltage required is 1.228 volts alternating current, at the 0 VU scale mark and 1.734 volts alternating current at full scale. The series 3,600 ohms is usually in the form of a suitable attenuator. These values are not direct reading, but are actually up 4 VU; hence the attenuator will read −4 VU at its point of zero attenuation.

If used in some special application where the potential is applied to the instrument directly, 0 VU will be indicated with 0.639 volt alternating current applied, and full scale, +3 VU, with 0.902 volt alternating current at the instrument terminals. The instrument resistance at the 0 VU scale mark is 3,900 ohms ±5% as measured with alternating current voltage by the voltage doubling method. It will be noted that the resistance is specified at 0 VU scale mark. This is because the resistance of a rectifier type instrument varies along the scale, being lowest at full scale and increasing down scale.

Voltage and resistance adjustments are at 1,000 cycles frequency. The tolerance over the audio frequency span of 25 to 16,000 cycles is held to close limits and the frequency error over this span can be ignored. Temperature error is within ±2% over the temperature range of +50F to +130F with negligible error at usual room temperatures of 65F to 95F.

Wherever random a-c currents are to be measured, the results will vary with the instrument dynamics. The VU indicator with its controlled dynamics is a common denominator for such work and may be used whenever its electrical characteristics fit the requirements.

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